

Enhanced response of soil respiration to experimental warming upon thermokarst formation

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1 **Supplementary Materials for**
2 **Enhanced response of soil respiration to experimental warming upon thermokarst**
3 **formation**

5 Wang et al.

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Supplementary Note 1. Calculations of apparent temperature sensitivity (Q_{10}) of soil respiration (Rs) and potential heterotrophic respiration (Rhp)

Based on observations over a seasonal scale, we determined apparent Q_{10} for both Rs and Rhp. Specifically, seasonal data of soil CO₂ flux and soil temperature were fitted to an exponential function¹:

$$R = ae^{bT} \quad (1)$$

where R is Rs or Rhp ($\mu\text{mol m}^{-2} \text{s}^{-1}$), T is soil temperature in the 0-10 cm layer ($^{\circ}\text{C}$), coefficient a is soil CO₂ flux at 0°C , and b is temperature response coefficient. The apparent Q_{10} for Rs or Rhp was then calculated using the following equation²:

$$Q_{10} = e^{10b} \quad (2)$$

where b is the temperature response coefficient and e is the natural base.

Supplementary Note 2. Comparison of Q_{10} derived from field experiment and laboratory incubation

The apparent Q_{10} obtained from the field experiment (non-collapsed *vs.* collapsed: 5.1 ± 0.1 *vs.* 7.2 ± 0.1 ; [Extended Data Fig. 6](#)) was much higher than that derived from the laboratory incubation (non-collapsed *vs.* collapsed: 2.2 ± 0.1 *vs.* 2.7 ± 0.2 ; [Fig. 2](#)), which might be associated with the discrepancy in methodology³. Laboratory incubation was conducted with more strict temperature control and thus the results revealed primarily temperature effect. While in the field condition, accompanied with temperature increase across seasons, alterations in environments, microbial characteristics and substrate supply etc. also existed³. Due to this point, the larger apparent Q_{10} observed in the field could be the consequence of interaction effects between temperature and other factors. First, vegetation productivity usually shows a similar seasonal pattern with temperature⁴. Correspondingly, elevated plant-derived substrate supplies with temperature increase would stimulate microbial respiration and its temperature response compared with the laboratory incubation where no fresh substrate was supplied⁵. Second, microbial biomass may also vary synchronously with temperature during the growing season⁶, and a greater microbial biomass would enhance the temperature effect on respiration rate^{7, 8}, likely favoring the higher apparent Q_{10} . Third, in spite of the critical role of soil moisture in mediating the apparent Q_{10} ⁹, the small fluctuations of soil moisture during the growing season ([Extended Fig. 5d-f](#)) might be less important for the higher apparent Q_{10} observed in our study site. Overall, these processes may lead to larger apparent Q_{10} values in the field conditions compared with

45 those derived from laboratory incubation.

Supplementary Note 3. Changes in soil physicochemical properties upon thermokarst formation

There were significant reductions of soil moisture, clay+silt, soil organic carbon (SOC) and total nitrogen (TN) in the top 10 cm upon thermokarst formation ([Supplementary Fig. 2](#)). The decreased soil moisture could be ascribed to the improved drainage after thermokarst formation¹⁰. The reduced clay+silt and SOC content were likely associated with water leaching and microbial degradation under permafrost collapse^{11, 12}. Specifically, thermokarst formation is commonly accompanied by water tracks or headwater streams¹³, which is also the case across our study sites. The formation of a headwater stream could cause the loss of clay+silt fraction by stimulating the erosion of finer materials compared with the sand component¹⁴. By the same token, a headwater stream would inevitably lead to SOC loss by lateral carbon (C) transport to the surrounding water^{12, 15}. Moreover, microbial activities involved in soil organic matter decomposition increased after permafrost collapse (as indicated by the increased Rs in our study; Fig. 1), and consequently reduced the SOC content¹⁶. Overall, the combination of water leaching and microbial degradation could be associated with the decreased clay+silt and SOC content upon thermokarst formation.

Our results also revealed that topsoil sand content, bulk density, inorganic phosphorus and organically complexed iron oxides (Fe_p) significantly increased after permafrost collapse ([Supplementary Fig. 2](#)). The increased sand content upon thermokarst formation corresponded to the decreased clay+silt content by water leaching, and was

68 generally accompanied by the increase in bulk density¹⁴. Meanwhile, soil inorganic
69 phosphorus availability increased with the enhancement of phosphate solubilization
70 and organic phosphorus mineralization⁴. In addition, with the improvement of aeration
71 due to soil drainage upon thermokarst formation, oxygen could replace Fe(III) as
72 electron acceptors during microbial respiration and stimulate the Fe(II) oxidation to
73 Fe(III), consequently linking to the accumulation of Fe_p^{15, 17}.

Supplementary Note 4. Calculations of warming-induced increases in soil respiration under thermokarst formation

We estimated additional soil CO₂ release induced by climate warming under thermokarst-affected areas according to the following five steps (Supplementary Fig. 6). First, we estimated the warming-induced additional soil CO₂ release per unit temperature change in the collapsed area (*i.e.*, Δm_{col}). Prior to calculation, we acquired the cumulative growing season soil CO₂ release in control and warming plots respectively in the collapsed area (*i.e.*, m) using the following equation:

$$m = \sum_{t=1}^{n-1} \left(\frac{R_t + R_{t+1}}{2} \times (d_{t+1} - d_t) \right) \quad (3)$$

where R_t and R_{t+1} are the *in situ* Rs (g C m⁻² day⁻¹) measured at time t and $t+1$ (day), $d_{t+1} - d_t$ is the time length between two adjacent measurements (day), n is the number of measurements during the growing season. Then the warming-induced additional soil CO₂ release per unit temperature change in the collapsed area (*i.e.*, Δm_{col}) was calculated as:

$$\Delta m_{col} = \frac{m_{warming} - m_{control}}{\Delta ST} \quad (4)$$

where $m_{warming}$ and $m_{control}$ are the cumulative growing season CO₂ release in warming and control plots (g C m⁻² yr⁻¹), ΔST is the average temperature difference between warming and control plots during the growing season (°C).

Second, similar to the collapsed area, we quantified warming-induced additional soil CO₂ release per unit temperature change in the non-collapsed area (*i.e.*, Δm_{n-col}) following the same procedure as described in the first step.

Third, we obtained the difference of warming-induced additional soil CO₂ release per unit temperature change between collapsed and non-collapsed areas (*i.e.*, Δm) using the following equation:

$$\Delta M = \Delta m_{col} - \Delta m_{n-col} \quad (5)$$

where Δm_{col} and Δm_{n-col} are the warming-induced additional soil CO₂ release per unit temperature change in collapsed and non-collapsed areas (g C m⁻² yr⁻¹ °C⁻¹), respectively.

Fourth, we assessed the additional soil CO₂ release under 2°C warming (*i.e.*, $\Delta M_{\Delta T}$) using the following equation:

$$\Delta M_{\Delta T} = \Delta M \times \Delta T \quad (6)$$

where ΔM is the thermokarst-induced additional CO₂ release per unit temperature change (g C m⁻² yr⁻¹ °C⁻¹), ΔT is the predicted temperature increase (2°C) given that permafrost regions were predicted to suffer a ~2°C warming under a moderate scenario by the end of 21st century¹⁸.

Finally, we upscaled the additional CO₂ release to the upland thermokarst region in the Northern Hemisphere (*i.e.*, $M_{addition}$) using the following formula:

$$M_{addition} = \Delta M_{\Delta T} \times S \quad (7)$$

where $\Delta M_{\Delta T}$ is the thermokarst-induced additional CO₂ release under 2°C warming (g C m⁻² yr⁻¹), S is the area of upland thermokarst landscape in the Northern Hemisphere, which is 0.91×10^6 km² as reported by ref. 19.

119

120 During the calculation processes mentioned above, we assumed that the upland
121 thermokarst landscape in the Northern Hemisphere had similar temperature response of
122 soil CO₂ release to climate warming as the upland thermokarst landscape occurring in
123 swamp meadow on the Tibetan Plateau, considering their similar cold environment and
124 SOC density (C amount per area, swamp meadow vs. upland thermokarst landscape: 65
125 vs. 74 kg C m⁻² in the top 3 m)^{19, 20}. We also assumed the same warming effects on soil
126 CO₂ release in bare soil and vegetated patches occurring within the thermokarst
127 landscape. To verify this point, we conducted additional measurements in both bare soil
128 and vegetated patches at the Shaliuhe site ([Supplementary Note 6](#)). Our results revealed
129 no significant difference in the normalized warming effect between bare soil and
130 vegetated patches ([Supplementary Fig. 10](#)), supporting our assumption.

Supplementary Note 5. Limitation of warming experiment involved in this study

The deployment of open top chamber (OTC) imposed an average of 1.3°C of soil warming in the top 10 cm during the growing season ([Extended Data Fig. 4](#)), which was within the range of other OTC warming experiments in permafrost ecosystems (less than 2°C)^{21, 22}. Nevertheless, despite a widely used method^{22, 23, 24}, the deployment of OTC would alter a series of physical environments (*e.g.* local wind shielding, rainfall interception, etc.) rather than only temperature, which may yield an enclosure bias of the additional CO₂ emission. To explore whether temperature could play a critical role in affecting soil CO₂ flux, we investigated linkages of warming-induced changes in Rs with the corresponding changes in various environmental factors. Our results showed that the response ratio (RR, the ratio of a variable in warming plots to that in control plots) of Rs only exhibited a positive correlation with that of topsoil temperature ([Supplementary Fig. 11](#)), indicating that temperature exerted the major role in affecting Rs at our study site. Nevertheless, in future studies, a more sophisticated warming approach is needed to avoid the potential shortcomings mentioned above. Apart from the above issues, given that subsoils are projected to warm at roughly the same rate as surface soils over the next century¹⁸, and could contribute to 10% of the warming response of Rs²⁵, the whole-soil-profile warming approach is needed for better understanding deep soil C dynamics in permafrost ecosystems under future warming.

Supplementary Note 6. Comparisons of Rs response to experimental warming between bare soil and vegetated patches

We conducted a supplementary experiment to compare the difference in the warming effects on Rs between bare soil and vegetated patches within the thermokarst landscape at the Shaliuhe site. Specifically, at the end of July 2023, five blocks including both bare soil and vegetated patches were randomly chosen from the collapsed area of one thermo-erosion gully, and the warming treatment was performed in both landforms of each block. Passive warming was implemented using the same OTC as described in the main text. *In situ* Rs was determined after an equilibration period (15 days) to reduce the disturbance of PVC collar deployment. The Rs measurement was conducted on 13 and 28 August 2023, using the same approach as mentioned in the main text.

Our measurements showed that experimental warming stimulated Rs in both bare soil and vegetated patches, with averages (mean $\pm$ standard error) of $62.3 \pm 10.0\%$ and $52.0 \pm 16.6\%$, respectively. We then calculated the normalized warming effects, and found that there was no obvious difference between the bare soil and vegetated patches ([Supplementary Fig. 10](#)). These results demonstrated a similar temperature sensitivity of Rs both landforms. Thus, the inclusion of bare soil may not have significant influence on the magnitude of thermokarst effects estimated in this study.

Supplementary Note 7. Soil physicochemical analyses

Soil total C and N concentrations were determined using Vario ElIII elemental analyzer (Elementar, Hanau, Germany). Given that soil inorganic C was negligible at the main site (Shaliuhe site, averaging 0.02% of total C, [Supplementary Fig. 12](#)), we used total C as a surrogate of SOC. For determining the concentration of inorganic N (sum of NH_4^+ -N and NO_3^- -N), fresh soil was extracted with 1 M KCl and analyzed using an Autoanalyzer 3 SEAL flow injection analyzer (Bran and Luebbe, Norderstedt, Germany). Soil inorganic phosphorus was determined based on the vanado-molybdate method²⁶. Soil pH was determined in a 1:5 soil:water suspension using a PB-10 pH electrode (Sartorius, Goettingen, Germany). Soil texture was analyzed using a Malvern Masterizer 2000 particle-size analyzer (Malvern, Worcestershire, UK) after thorough removal of organic matter and carbonate using 30% H_2O_2 and 30% HCl. Soil bulk density was determined using a stainless-steel cylinder with a fixed volume of 100 cm^3 , and calculated as the ratio of the 105°C-oven-dried soil mass to the container volume. The water-filled pore space (WFPS, %) was calculated as^{14, 27}:

$$\text{WFPS} = (\text{SWC} \times \text{BD}) / (1 - \text{BD} / \text{PD}) \quad (8)$$

where SWC is gravimetric moisture content (%), BD is bulk density (g cm^{-3}), and PD is particle density (2.65 g cm^{-3}).

Supplementary Note 8. Measurements of soil enzyme activity

We analyzed the activities of four extracellular hydrolases, β -1,4-glucosidase (BG), β -1,4-N-acetyl-glucosaminidase (NAG), leucine aminopeptidase (LAP), and phosphatase (AP) using fluorescence measurements²⁸, as well as the activity of one extracellular oxidase (phenol oxidase) using spectrophotometry according to ref. 29. Specifically, soil suspensions combined with specific substrates (4-methylumbelliferone (MUB)- β -D-glucoside for BG, 4-MUB-*N*-acetyl- β -D-glucosaminide for NAG, *L*-leucine-7-amino-4-methylcoumarin for LAP and 4-MUB phosphate for AP) were added to 96-well microporous plates and incubated at 15°C (similar to the highest monthly average temperature at the main site of Shaliuhe) for 3 h in the dark. The fluorescence of the mixture was then measured using a DTX 880 Multimode Detector (Beckman Coulter Inc., Fullerton, USA) at 365 nm (excitation) and 450 nm (emission)²⁸. Standard curves were established by adding various concentrations of standard solutions (4-MUB for BG, NAG and AP, and 7-amino-4-methylcoumarin for LAP) to each sample. The fluorescence was converted based on the standard curve to calculate hydrolase activity, and all four hydrolase activities were summed as the total hydrolase activity. Oxidase activity was spectrophotometrically determined³⁰. The soil suspension, EDTA and *L*-3,4-dihydroxy-phenylalanine were added to the microplates, which were incubated at 15°C for 20 h. The mixtures were then passed through the Multimode Detector to measure the absorbance at 450 nm. Enzyme activity was calculated as nmol g⁻¹ h⁻¹.

Supplementary Note 9. Bioinformatic analyses for high-throughput sequencing

We conducted bioinformatic analyses as follows: raw paired sequences were merged using FLASH (v. 1.2.11, <https://ccb.jhu.edu/software/FLASH/>) with a minimum overlap of 10 bp and allowable error ratios < 0.2 . The merged sequences were then quality controlled using Trimmomatic to remove low-quality reads³¹. Chimeras were detected and removed using UCHIME (v. 8.1)³². Clean sequences with 97% nucleotide identity were subsequently clustered into operational taxonomic units (OTUs) using USEARCH (v. 11)³³. The most abundant sequence within each OTU was defined as the representative sequence. Taxonomic information for each representative OTU was then annotated with confidence thresholds ≥ 0.6 using the Silva v. 123 (for the 16S rRNA gene)³⁴ and Unite v. 7.1 (for the ITS rRNA gene)³⁵ databases. We removed OTUs identified as non-bacterial OTUs in the 16S rRNA gene sequencing and non-fungal OTUs in the ITS rRNA gene sequencing. OTU tables for bacteria and fungi were rarefied at the minimal sequence number per sample of each table to ensure an even sampling depth.

222 **Supplementary Table 1. Characteristics of the six thermokarst sites on the Tibetan Plateau.**

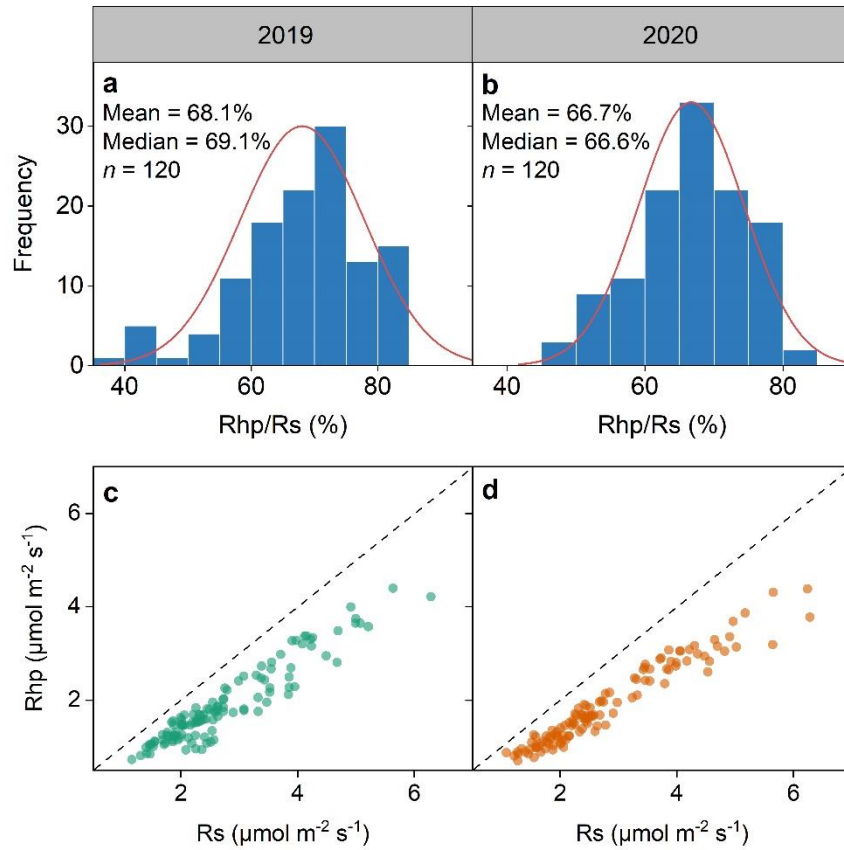
Site	Lat. (°N)	Long. (°E)	El. (m)	MAT (°C)	MAP (mm)	Vegetation type	Soil type	Thermokarst type	ALT (cm)
EB	38.0	100.9	3650	2.6	367	Swamp meadow	Cryosols	Thermo-erosion gully	79.3
ML	37.8	100.8	3760	1.4	411	Swamp meadow	Cryosols	Thermo-erosion gully	91.2
RS	37.7	100.4	3580	3.7	493	Swamp meadow	Cryosols	Thermo-erosion gully	85.9
SLH	37.5	100.3	3847	0.1	402	Swamp meadow	Cryosols	Thermo-erosion gully	72.7
HSX	35.1	98.7	4460	-1.0	353	Swamp meadow	Cryosols	Thermo-erosion gully	54.6
HH	34.3	97.9	4707	-3.1	436	Swamp meadow	Cryosols	Thermo-erosion gully	73.9

223 Abbreviations: EB, Ebo site; ML, Mole site; RS, Reshui site; SLH, Shaliuhe site; HSX, Huashixia site; HH, Huanghe site; Lat., latitude; Long.,
224 longitude; El., elevation; MAT, mean annual temperature; MAP, mean annual precipitation; ALT, active layer thickness; The MAT and MAP
225 were originally derived from the National Meteorological Information Center (<http://data.cma.cn/en>), and estimated for each thermokarst site based
226 on Kriging interpolation³⁶. Soil type was classified based on the World Reference Base for Soil Resources³⁷.

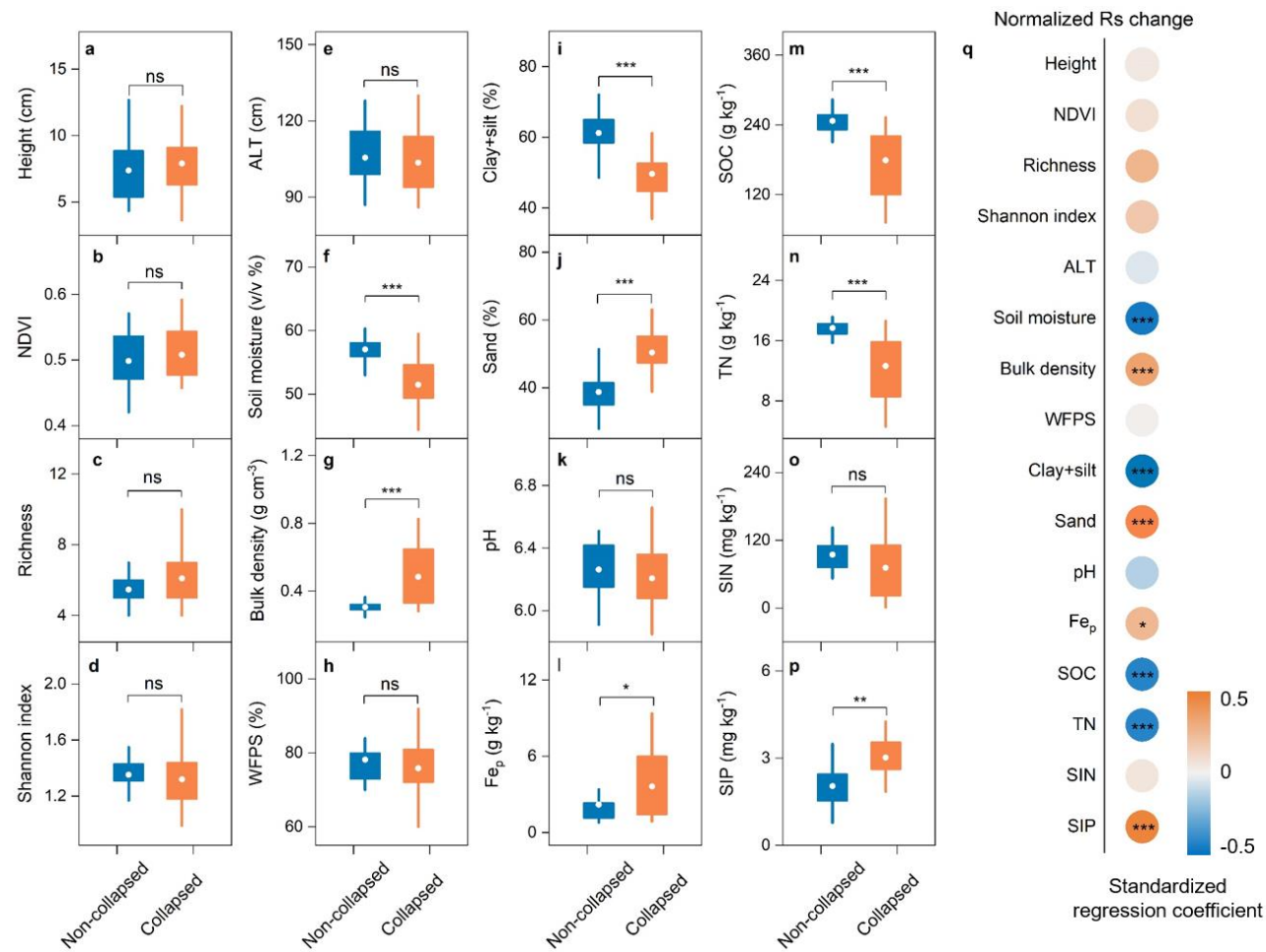
Supplementary Table 2. Results of the principal component analysis of substrate quality and microbial functional gene abundances.

	Loading	Correlation coefficient
Substrate quality		
Alkyl	0.49	0.78***
O-alkyl	-0.58	0.55***
Alkyl/O-alkyl	-0.65	0.99***
Proportion of variance		77.6%
Microbial functional genes		
Hemicellulose	0.51	0.73***
Pectinase	0.38	0.67***
Aromatics	0.14	0.26***
Proportion of variance		86.1%

Loading, correlation coefficient and proportion of variance explained by the principal components are shown for substrate quality with the first component of principal component analysis, and for microbial functional genes with the average of the first and second component. ***, $P < 0.001$.



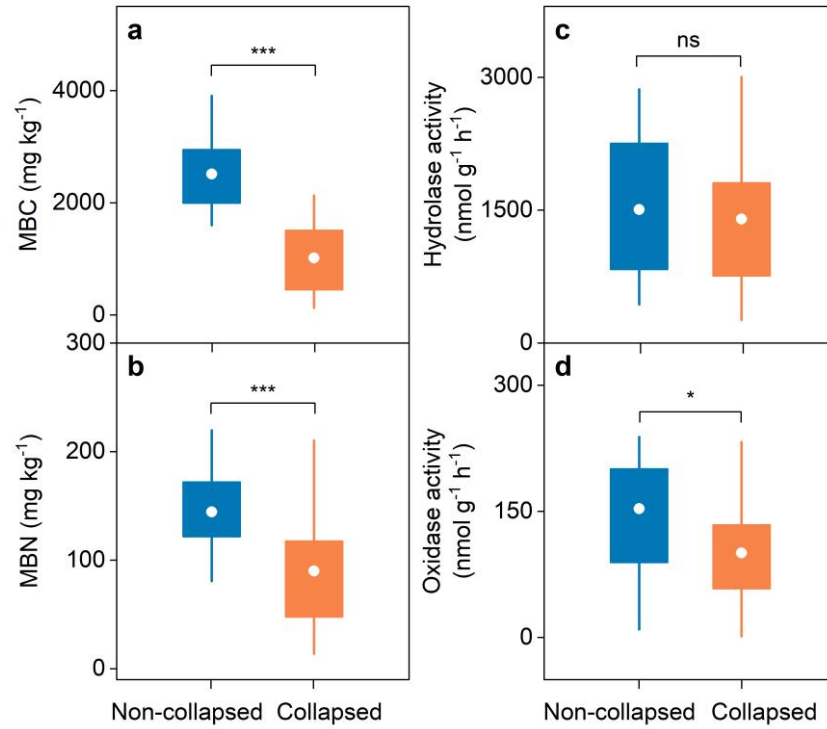
Supplementary Fig. 1 | Frequency distributions of the proportion of potential heterotrophic respiration to soil respiration (Rhp/Rs) and scatter plots of Rhp vs. Rs using data from the Shaliuhe site in 2019 and 2020. a,b, Frequency distributions of Rhp/Rs data measured in 2019 (a) and 2020 (b). **c,d,** Scatter plots of Rhp vs. Rs using data measured in 2019 (c) and 2020 (d). The dashed line indicates 1:1 line.



239

240 **Supplementary Fig. 2 | Thermokarst-induced differences in vegetation and soil properties in the top 10 cm and their associations with the**

241 **normalized soil respiration (Rs) change at the Shaliuhe site. a-p**, Differences in plant height (**a**), Normalized Difference Vegetation Index
242 (NDVI, **b**), richness (**c**), Shannon index (**d**), active layer thickness (ALT, **e**), soil moisture (**f**), bulk density (**g**), water filled pore space (WFPS, **h**),
243 contents of clay+silt (**i**) and sand (**j**), pH (**k**), organically complexed Fe oxides (Fe_p, **l**), soil organic carbon (SOC, **m**), total nitrogen (TN, **n**), soil
244 inorganic nitrogen (SIN, **o**), and soil inorganic phosphorus (SIP, **p**). The ends of the boxes represent the 25th and 75th percentiles, and whiskers
245 refer to the 10th and 90th quartiles. The white dot in each box represent the average. **q**, Standardized regression coefficient of the relationships of
246 the normalized Rs change with abiotic and biotic factors. The color scale indicates the strength and sign of the correlations. Significant differences
247 between collapsed and non-collapsed areas were determined based on linear mixed-effects models. ns, non-significant; *, $P < 0.05$; **, $P < 0.01$;
248 ***, $P < 0.001$. These parameters were determined across the three thermo-erosion gullies in 2019.



Supplementary Fig. 3 | Thermokarst-induced differences in topsoil (0-10 cm)

microbial biomass and enzyme activities at the Shaliuhe site. a-d, Differences in

MBC (a), MBN (b), activities of hydrolase (c) and oxidase (d) between collapsed and

non-collapsed areas. The ends of the boxes represent the 25th and 75th percentiles, and

the whiskers refer to the 10th and 90th quartiles. The white dot in each box represent the

average. MBC, microbial biomass carbon; MBN, microbial biomass nitrogen.

Hydrolase activity, the sum of activities of β -1,4-glucosidase (BG), β -1,4-N-acetyl-

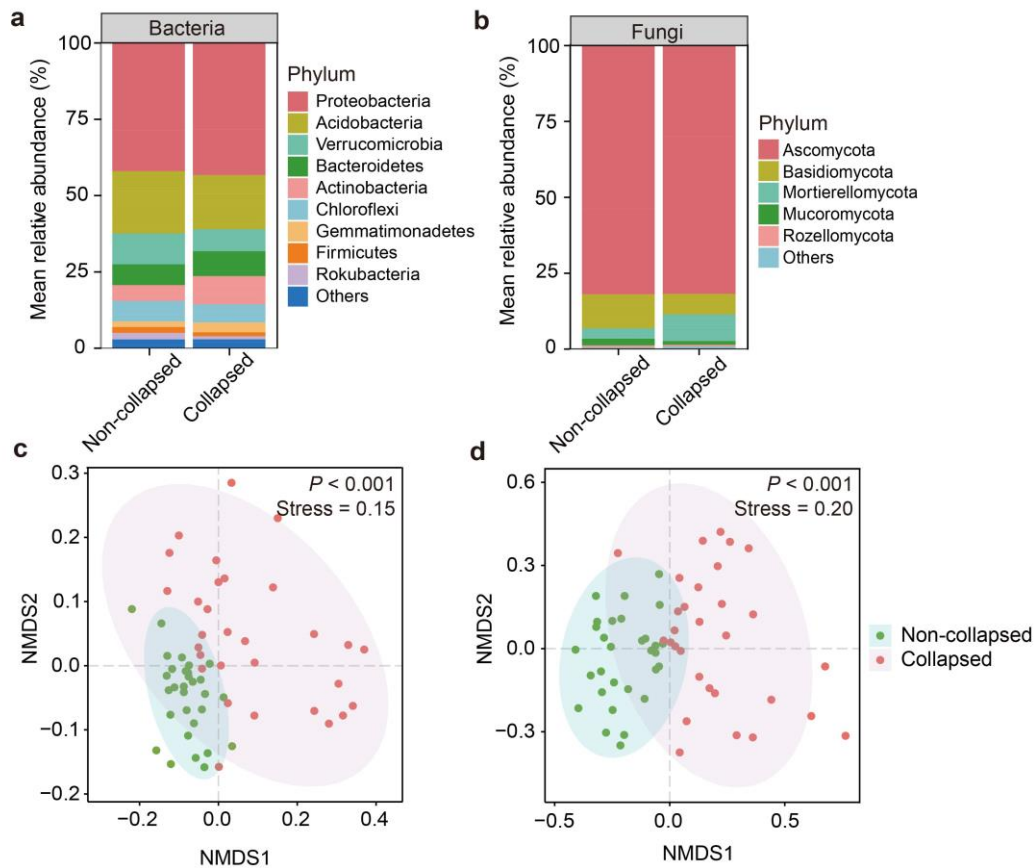
glucosaminidase (NAG), leucine aminopeptidase (LAP), and phosphatase (AP);

Oxidase activity, phenol oxidase activity. Significant differences between collapsed

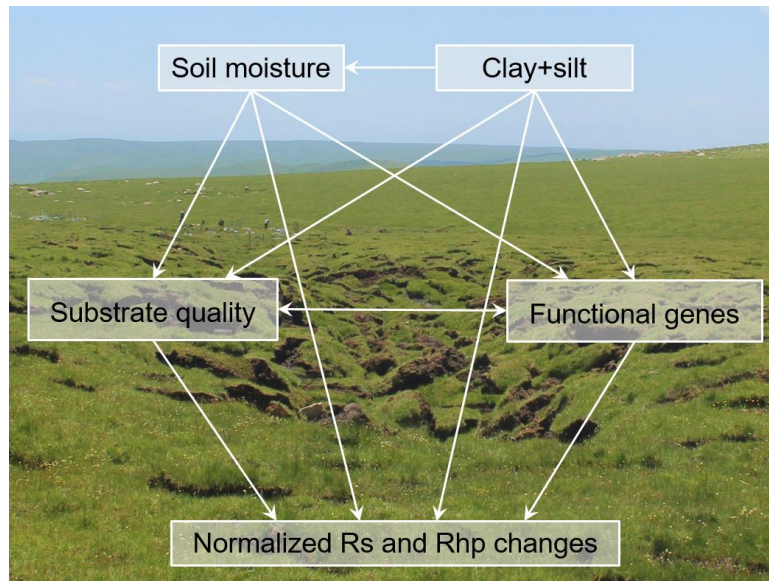
and non-collapsed areas were determined based on linear mixed-effects models. ns,

non-significant; *, $P < 0.05$; ***, $P < 0.001$. Samples were collected from the three

thermo-erosion gullies at the Shaliuhe site in 2019.



Supplementary Fig. 4 | Thermokarst-induced shifts in topsoil (10 cm) microbial communities at the Shaliuhe site. a,b, Relative abundance of the phyla in bacterial (a) and fungal (b) communities in collapsed and non-collapsed areas. **c,d,** Results of the permutational multivariate analysis of variance (PERMANOVA) for bacterial (c) and fungal (d) communities visualized by nonmetric multidimensional scaling ordination (NMDS). The PERMANOVA was employed to identify significant differences in the microbial communities between the collapsed and non-collapsed areas. The stress values of the NMDS are shown at the top right of each panel. Samples were collected from the three thermo-erosion gullies in 2019.



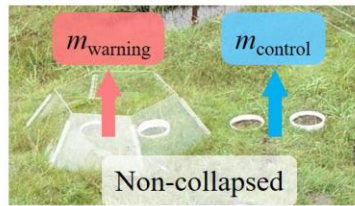
Supplementary Fig. 5 | Initial structural equation models of the normalized responses of soil respiration (Rs) and potential heterotrophic respiration (Rhp) to experimental warming. The background photograph shows thermokarst landscape at the Shaliuhe site. Photograph credit: G.Q. Wang.

Step 1 In collapsed area, warming-induced additional CO₂ release per unit temperature change was calculated as the difference of cumulative CO₂ release during the growing season between warming and control plots divided by the increasing temperature:



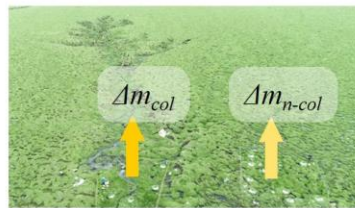
$$\Delta m_{col} = \frac{m_{warming} - m_{control}}{\Delta ST}$$

Step 2 In non-collapsed area, warming-induced additional soil CO₂ release per unit temperature change was calculated following the same procedure executed in collapsed area:



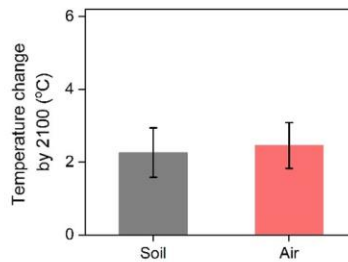
$$\Delta m_{n-col} = \frac{m_{warming} - m_{control}}{\Delta ST}$$

Step 3 Difference of warming-induced additional CO₂ release between collapsed and non-collapsed areas was calculated as:



$$\Delta M = \Delta m_{col} - \Delta m_{n-col}$$

Step 4 The additional soil CO₂ release under 2°C warming was assessed using the following equation:



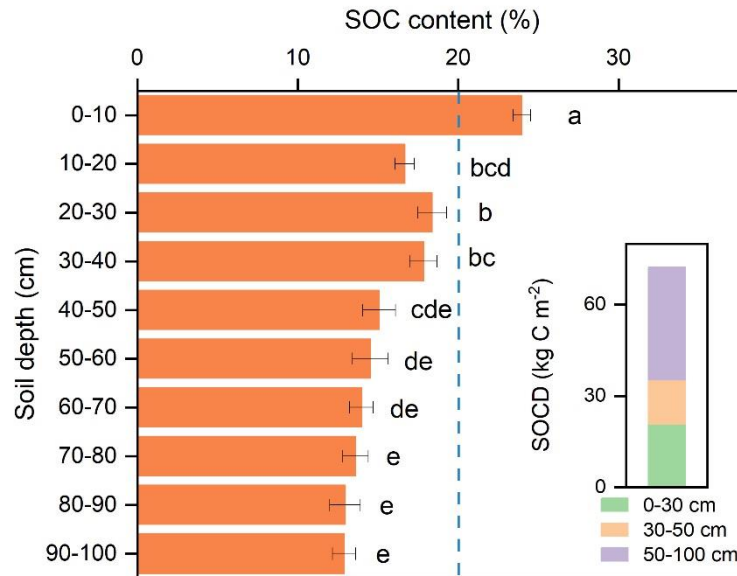
$$\Delta M_{2^{\circ}C} = \Delta M \times 2^{\circ}C$$

2 °C is the warming magnitude in permafrost regions by the end of 21st century under a moderate scenario (Soong et al. 2020)

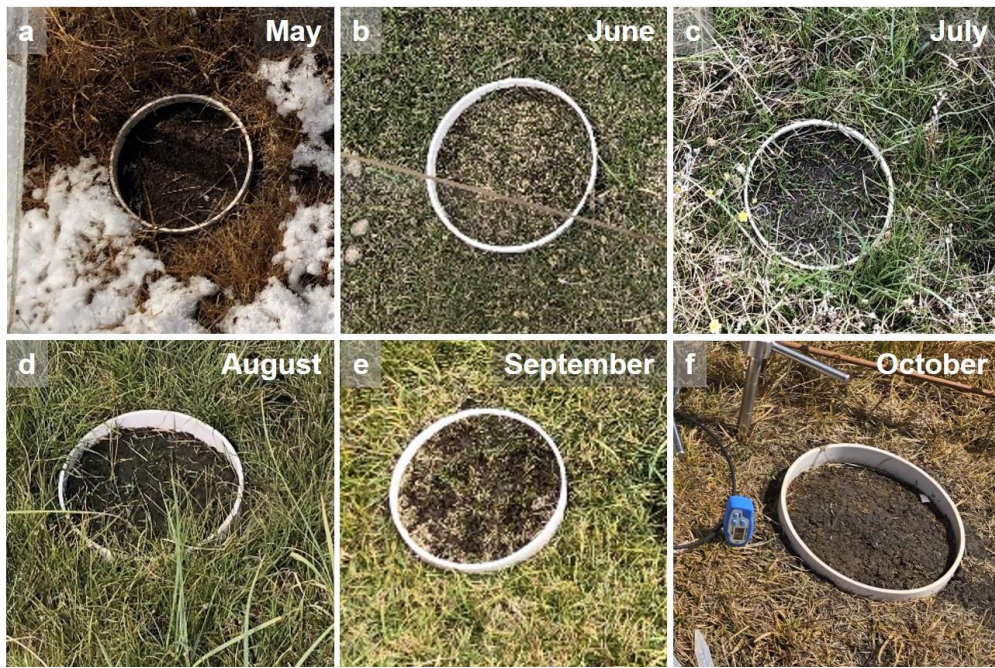
Step 5 Additional CO₂ release was extrapolated to the upland thermokarst region of the Northern Hemisphere with the area of 0.91 × 10⁶ km² estimated by Olefeldt et al. (2016):

$$M_{addition} = \Delta M_{2^{\circ}C} \times S$$

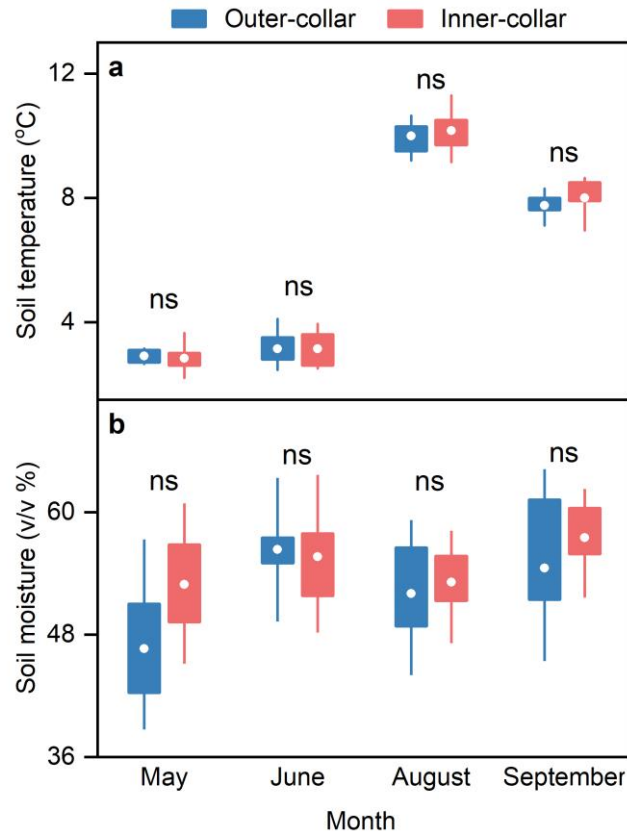
Supplementary Fig. 6 | Flow chart showing key steps of estimating additional CO₂ release from upland thermokarst area in the Northern Hemisphere under a future warming scenario. Data involved in steps 4 and 5 were retrieved from ref. 18 and ref. 19, respectively. Photograph credit: G.Q. Wang.



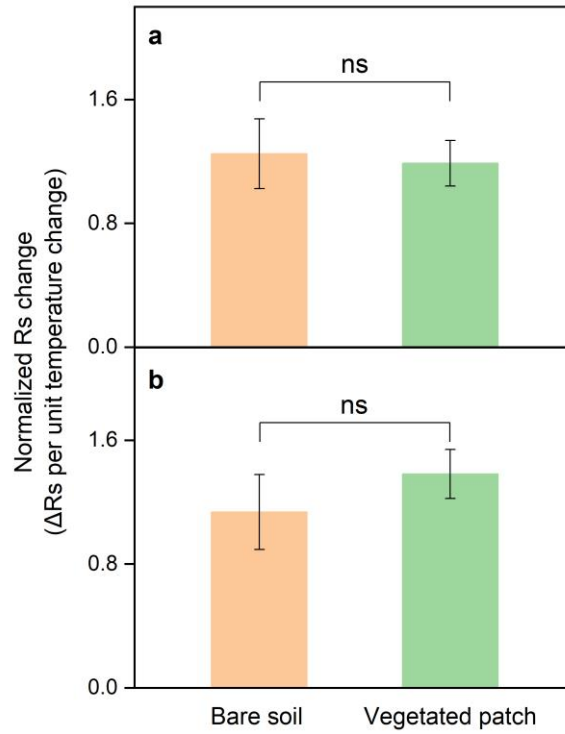
Supplementary Fig. 7 | Vertical distribution of soil organic carbon (SOC) content of the non-collapsed area at the Shaliuhe site. Error bars denote standard errors. The dashed line shows the 20% SOC content. Significant differences among soil depths were determined based on one-way ANOVA and indicated by different letters. The insert shows the cumulative SOC density (carbon amount per area, SOCD) at depths of 30, 50 and 100 cm. These data were reanalyzed from ref. 38.



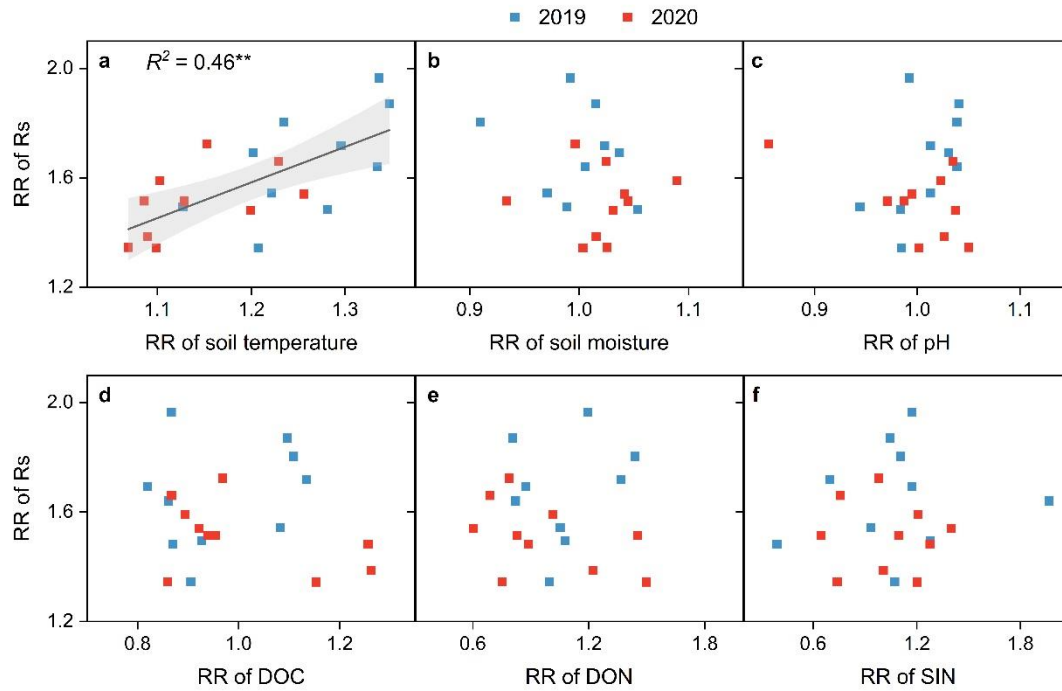
Supplementary Fig. 8 | Photographs showing the status of soil collars at the Shaliuhe site during soil respiration measurements. a-f, Status of collars and the surrounding soils in different months of the growing season in 2019. Photograph credit: G.Q. Wang.



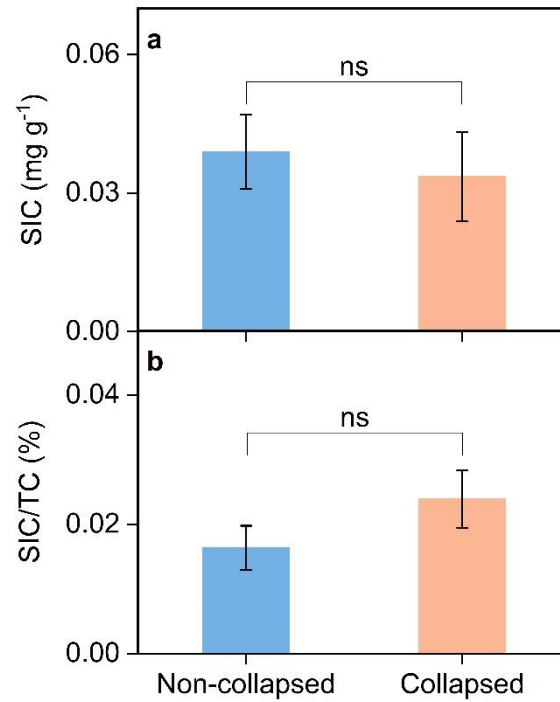
Supplementary Fig. 9 | Comparisons of topsoil (0-10 cm) temperature (a) and moisture (b) inside and outside the collars at the Shaliuhe site. The ends of the boxes represent the 25th and 75th percentiles, and whiskers represent the 10th and 90th quartiles. The white dot in each box represent the average. Significant differences between outer- and inner-collars were determined based on two-sided *t* tests. ns, non-significant. Both soil temperature and moisture were measured during the growing season in 2019.



Supplementary Fig. 10 | Warming effects on soil respiration (Rs) between bare soil and vegetated patches at the Shaliuhe site for the first (a) and second (b) measurements in August 2023. Error bars denote standard errors. Differences between bare soil and vegetated patches were determined based on two-sided *t* tests. ns, non-significant.



Supplementary Fig. 11 | Relationships between warming-induced changes in soil respiration (Rs) and changes in environmental factors at the Shaliuhe site. a-f, Relationships of the response ratio (RR, the ratio of a variable in warming plots to that in control plots) of Rs with RRs of soil temperature (**a**), soil moisture (**b**), pH (**c**), soil dissolved organic carbon (DOC, **d**), dissolved organic nitrogen (DON, **e**) and soil inorganic nitrogen (SIN, **f**) across the two experimental years (2019 and 2020). The linear regression lines with 95% confidence intervals reflect the predicted effects of fixed factors. **, $P < 0.01$.



Supplementary Fig. 12 | Topsoil (0-10 cm) inorganic C (SIC, a) content and its proportion of total C (TC, b) content at the Shaliuhe site. Error bars denote standard errors. Significant differences between collapsed and non-collapsed areas were determined based on two-sided *t* tests. ns, non-significant.

References

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